

# **STARCAM**

## **FINAL REPORT**

MSFC order # H30747D.  
UAH acct # 5-20383

Wesley Swift  
October 30 1999

# **STARCAM FINAL REPORT**

## **Project Goals**

This project can be defined by its three phases. The goals of Phase A of this contract are to (1) Determine the required dynamic range of the combined sky and stellar image and to (2) Specify camera and optics. That was accomplished and reported in the Phase A report attached. The goals of Phase B of this contract are to 1) Produce and demonstrate algorithms for starfield background removal, 2) Produce and demonstrate star tracking and centroiding algorithms, 3) Prepare and demonstrate pointing and auto-focus algorithms, and 4) Consult with those who develop flight software on above algorithms. We are pleased to report that the above has been accomplished and delivered to NASA via our contracting contact for this project, Cheryl Alexander and are attached here. We are proud to present this final report with the expectations that all should work as planned and under budget as well: two cameras for the expected price of one.

## **Phase C Goals: Optical Testing**

The original timeline for the project included in Phase C the assembly of the system, qualification testing, and platform integration. These items are either the responsibility of others or cannot be accomplished within the time constraints of this contract due to the rescheduling of the flight to the spring of 2000. The mutually agreed upon solution, as detailed in Appendix A, was for this consultant to be responsible for the optical lab testing of the assembled system and to recommend any changes necessary to ensure operability in flight. Furthermore, due to the reduced cost of the resulting system, it was decided for there to be two systems assembled and tested to ensure a flight backup.

We are happy to report that Optical Laboratory Testing has concluded successfully with the assurance that both camera system will deliver sharp star images. The differences between the cameras are slight but measurable with camera A to be preferred due to its tighter focus and fewer stepper motor problems. Camera B, however, has smoother flatfield response, which would make it preferred for photometry but is not

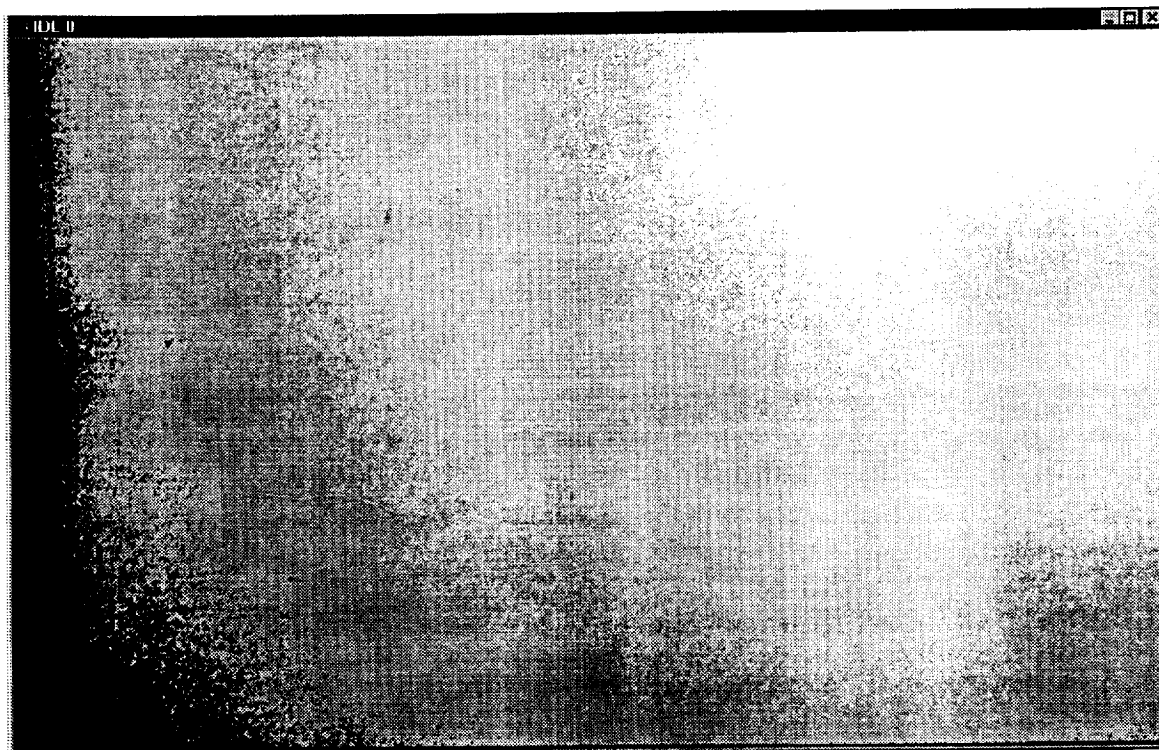
particularly relevant in stellar location work. The simple auto-focus algorithm suggested provides for ample sensitivity to achieve tight focus. At focus, the full width at half maximum of both cameras is of the order of two pixels, essentially the Niquist limit for pixilated images. This is reinforced by the images obtained from USAF target tests. Such a tight focus is hard to accomplish manually.

Several problems were discovered as part of above testing and had simple, readily implemented solutions. Chief of the problems resolved was the mechanical instability of the lens mount, which precluded our initial tests. Making a bracket for the front of the lens to provide excellent mechanical stability solved this. The other problem was with the stepper motor system: It lost track of position. This was solved by (1) loosening the clamp on the focuser coupling to reduce drag and (2) increasing the stepper drive current to closer to the motor's specifications. It is anticipated that full rated motor current will be required while in motion at the low temperatures encountered in flight.

# Flatfield Testing and Flatfield Production

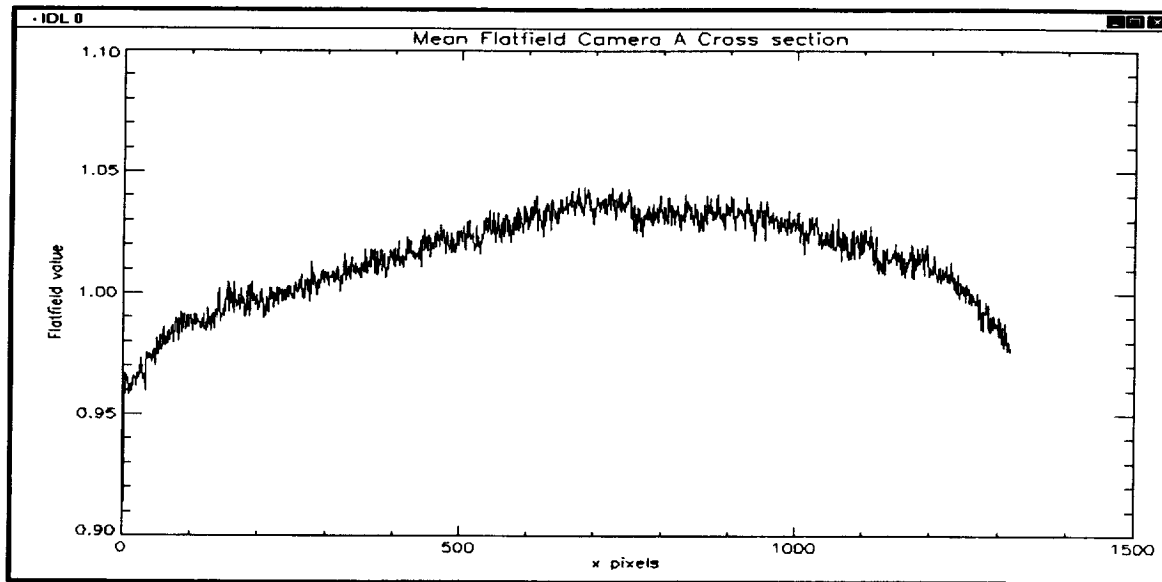
## Camera A Flatfields

Flatfields were prepared by exposing the camera focused at infinity to a  $\text{BaSO}_4$  screen illuminated at standard distance by a NTS traceable standard quartz iodide lamp maintained under regulated conditions. The screen was placed near the entrance pupil of the lens to essentially eliminate the small (less than 1%) variations in the intensity across the screen. Exposure was just below saturation to minimize digitization errors. The resulting variations across the image plane are thus due to (1) the fall off of the lens with increasing field of view and (2) variations in sensitivity across the CCD due to manufacturing variations and (3) pixel to pixel variations. Flatfields were made using four different filters with no significant difference. It is suggested that the mean flatfield be used normalized about the mean value so as to leave the total image counts unchanged. The result is an image with  $\pm 5\%$  variation about unity. In use, the data image is divided by this flatfield image pixel by pixel resulting in an image with the lens falloff, CCD variations and pixel variations removed. The data is located at: <ftp://iso.uah.edu/starcam/camA/camafats.xdr> and is in IDL saveset format. The suggested flatfield for camera A is in <ftp://iso.uah.edu/starcam/camA/meanflata.xdr> in the same format. For stellar centroiding purposes, only the pixel to pixel variations are of significance.



Flatfield image camera A, 89b filter

Note the CCD fall off from the upper right corner and the slight discontinuity at the right. The texture in this enhanced image is due to the pixel to pixel variations.



Normalized flatfield for Camera A, average over all filters

The above cross section shows the curvature due to the lens falloff as well as the pixel to pixel variations. The “bumps” are CCD variations.

Camera A mean flatfield statistics:

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Mean Flatfield Camera A

MIN: 0.619921 MAX: 1.05106

MEAN: 1.00108 MEDIAN: 1.00254

STD: 0.0251075 N PTS: 1363095

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These are the flatfields for camera A at various gains with various filters as given in array form in the file <ftp://iso.uah.edu/starcam/camA/camaflats.xdr>

cam A gain 1 filter none	cam A gain 2 filter none	cam A gain 3 filter none
cam A gain 1 filter R25a	cam A gain 2 filter R25a	cam A gain 3 filter R25a
cam A gain 1 filter #89b	cam A gain 2 filter #89b	cam A gain 3 filter #89b
cam A gain 1 filter #87	cam A gain 2 filter #87	cam A gain 3 filter #87
cam A gain 1 filter Y25	cam A gain 2 filter Y25	cam A gain 3 filter Y25

Saving to file CAMaflats.xdr

In directory d:\starcam\camaflat and in <ftp://iso.uah.edu/starcam/camA/>

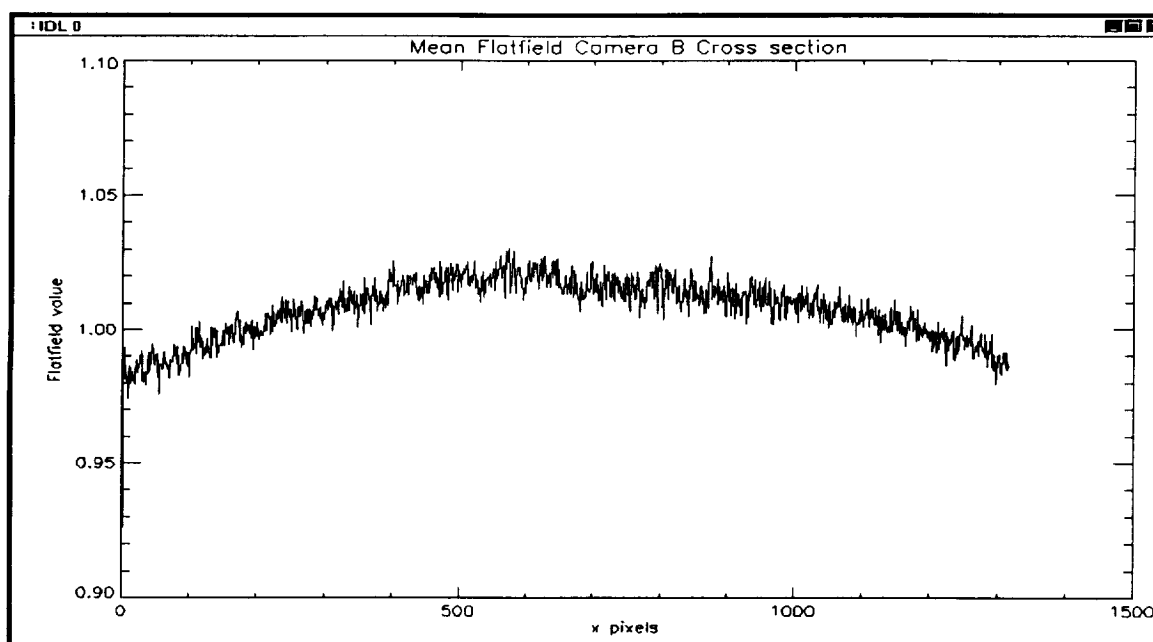
## Camera B Flatfields

Flatfields for camera B were prepared by exposing the camera focused at infinity to a BaSO<sub>4</sub> screen illuminated at standard distance by a NTS traceable standard quartz iodide lamp maintained under regulated conditions. The screen was placed near the entrance pupil of the lens to essentially eliminate the small (less than 1%) variations in the intensity across the screen. Exposure was just below saturation to minimize digitization errors. The resulting variations across the image plane are thus due to (1) the fall off of the lens with increasing field of view and (2) variations in sensitivity across the CCD due to manufacturing variations and (3) pixel to pixel variations. Flatfields were made using four different filters with no significant difference. It is suggested that the mean flatfield be used normalized about the mean value so as to leave the total image counts unchanged. The result is an image with +/- 3% variation about unity. In use, the data image is divided by this flatfield image pixel by pixel resulting in an image with the lens falloff, CCD variations and pixel variations removed. The data is located at: <ftp://iso.uah.edu/starcam/camB/cambflats.xdr> and is in IDL saveset format. The suggested flatfield for camera B is in <ftp://iso.uah.edu/starcam/camB/meanflatb.xdr> in the same format. For stellar centroiding purposes, only the pixel to pixel variations are of significance.



Flatfield image camera B, 89b filter

Note the very small CCD fall off from the upper right corner and the slight discontinuity at the right. The texture in this enhanced image is due to the pixel to pixel variations.



The above cross section shows the small curvature due to the lens falloff as well as the pixel to pixel variations. The small “bumps” are CCD variations. Camera B is photometrically much smoother than camera A.

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Mean Flatfield Camera B

MIN: 0.650346 MAX: 1.03586  
 MEAN: 0.997221 MEDIAN: 1.00118  
 STD: 0.0181830 N PTS: 1363095

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These are the flatfields for camera b at various gains with various filters

cam B gain 1 filter none   cam B gain 2 filter none   cam B gain 3 filter none  
 cam B gain 1 filter R25a   cam B gain 2 filter R25a   cam B gain 3 filter R25a  
 cam B gain 1 filter #89b   cam B gain 2 filter #89b   cam B gain 3 filter #89b  
 cam B gain 1 filter #87   cam B gain 2 filter #87   cam B gain 3 filter #87  
 cam B gain 1 filter Y25   cam B gain 2 filter Y25   cam B gain 3 filter Y25

Saving to file CAMbflats.xdr

In directory d:\starcam\camB\flat and <ftp://iso.uah.edu/starcam/camB/>

% SAVE: Portable (XDR) SAVE/RESTORE file.

% SAVE: Saved variable: README.

% SAVE: Saved variable: FLAT\_DESCRIPTOR.

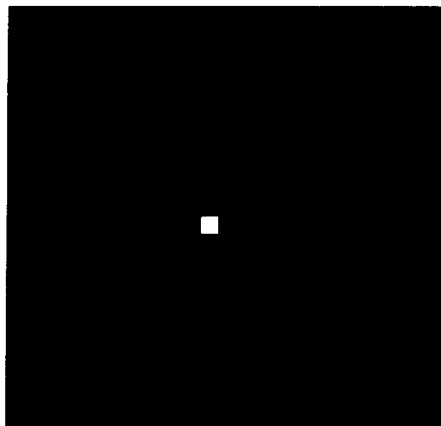
% SAVE: Saved variable: FLATSET.

# Collimator Star Testing / Focus Testing

For these tests, an artificial star was created by placing a polished metal sphere of about 3mm diameter at the focus of a 2718mm focal length reflective collimator. The sphere was illuminated with a pinhole about 2cm away. A telescope calibrated for this purpose checked the apparent object distance. When the artificial star was examined with a telescope of 50mm aperture, the through focus “star test” pattern implied that the star was equal to or smaller than the resolution limit of the telescope which is about 2.5 arc seconds. This is significantly smaller than the pixel size with a 180mm camera lens.

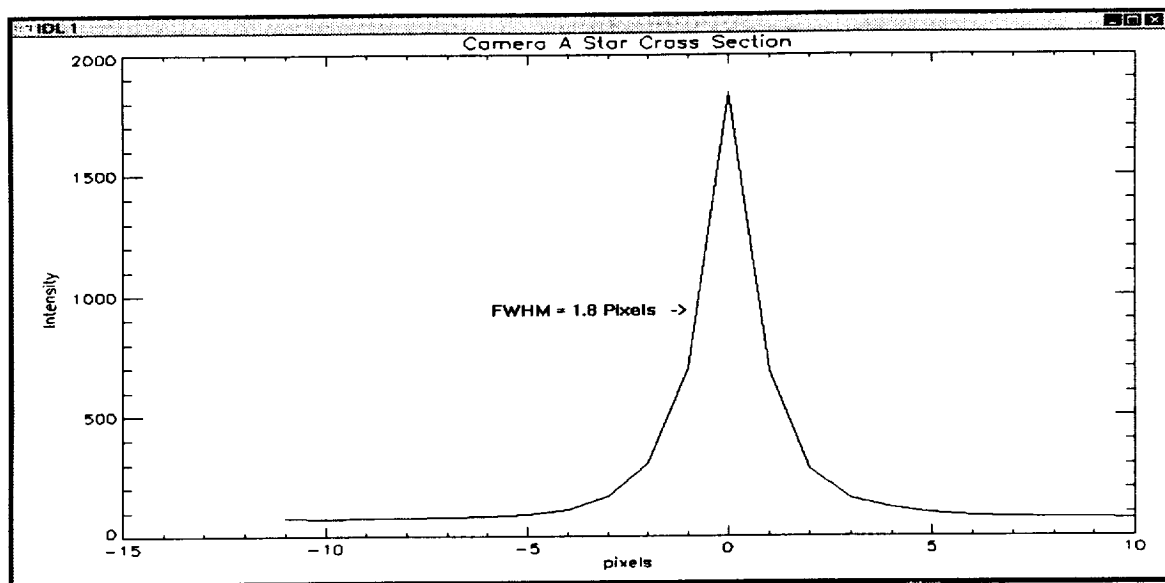
## Camera A Star Tests

When the artificial star image from the best focus position, image, rfa1970.tif , is examined on a pixel by pixel basis, as in the following figure, it is immediately apparent that a significant fraction of the photons are being put into one pixel. The pixels immediately adjacent to the central pixel have less than half the intensity of the peak pixel and the intensity falls off rapidly after that. Furthermore, the image is essentially symmetrical, which suggests little aberration. A cross section through the image, the next figure below, in the x (horizontal) direction shows the image to be essentially gaussian with a FWHM of about 1.8 pixels. This is consistent with the results from the USAF resolution target test for camera A below.



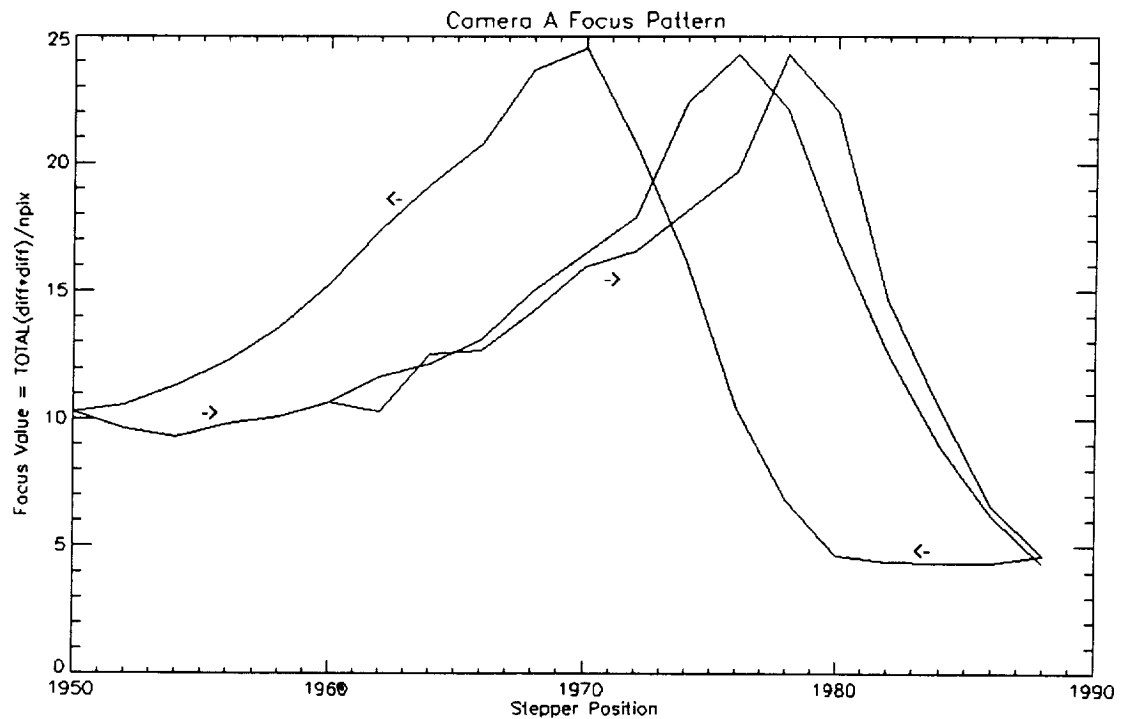
Pixel resolved image of artificial star





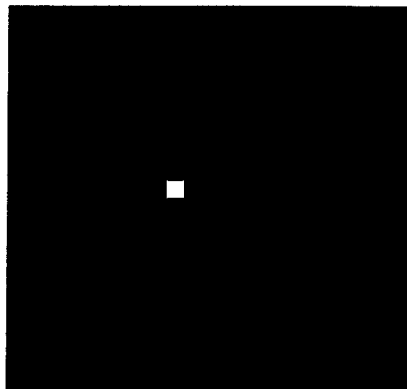
## Camera A Focus Tests

These tests were performed by resetting the focuser stepper motors at the home position, stepping rapidly forward to an assumed starting point and exposing a subframe which included the "collimator star". The steppers were then incremented by two steps and another exposure was taken and so forth until the point of best focus had been sufficiently passed. The stepper was then reversed and the series continued in the reverse direction and so on. The data was analyzed using a scaled shift-difference focus quality algorithm as a function of stepper position. The result was a sharp peak in the focus parameter shifted by the "slop" in the focuser mechanics. This slop, 8 pixels for camera A, was generally repeatable with the exception of evidence of some slippage of the stepper motor position at the first of this series as shown in the figure below. In the absence of such slippage, the focusing algorithm is simple: start short of the expected focus point, step past the peak by the slop in the system then step back by twice the slop.

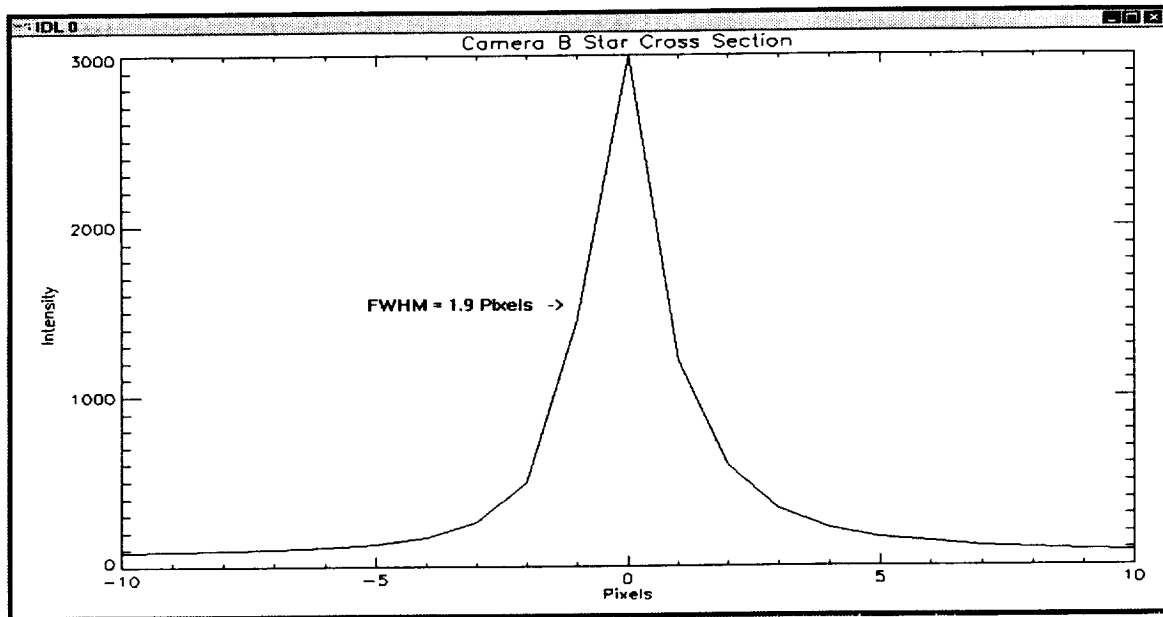


## Camera B Star Tests

When the artificial star image from the best focus position, image, ffb1960.tif, is examined on a pixel by pixel basis, as in the following figure, it is immediately apparent that a significant fraction of the photons are being put into one pixel. The pixels immediately adjacent to the central pixel have half the intensity of the peak pixel and the intensity falls off rapidly after that. Furthermore, the image is almost symmetrical, which suggests little aberration. A cross section through the image, the next figure below, in the x (horizontal) direction shows the image to be essentially gaussian with a FWHM of about 1.9 pixels. This is marginally broader than the best for Camera A above. This is consistent with the results from the USAF resolution target test for camera B below.



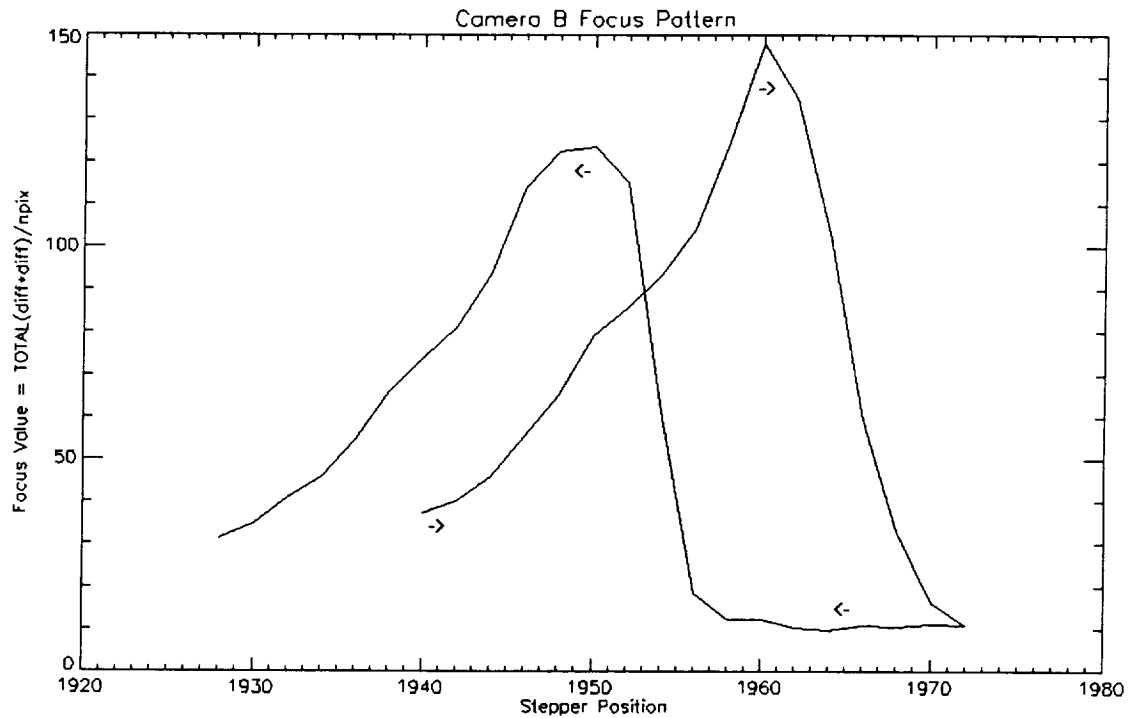
Pixel resolved image of artificial star



## Camera B Focus Tests

These tests were performed as above by resetting the focuser stepper motors at the home position, stepping rapidly forward to an assumed starting point and exposing a subframe which included the "collimator star". The steppers were then incremented by two steps and another exposure was taken and so forth until the point of best focus had been sufficiently passed. The stepper was then reversed and the series continued in the reverse direction and so on. The data was analyzed using a scaled shift-difference focus quality algorithm as a function of stepper position. The result was a sharp peak in the focus parameter shifted by the "slop" in the focuser mechanics. This slop, 12 pixels for camera B, was generally repeatable with the exception of evidence of some slippage of the stepper motor position at the first of this series as shown in the figure below. In the absence of such slippage, the focusing algorithm is as described above: start short of the expected focus point, step past the peak by the slop in the system then step back by twice the slop.

The main differences between the cameras besides the slop, were in the trouble we had with the stepper motors loosing track of position. The first attempts at producing a repeatable focus series were thwarted by an overly tightened focuser band clamp that caused excess drag in the system. Loosening the clamp was a definite improvement, but the motor currents had to be increased for reliable operation. The original current feedback resistor for both cameras was 100 ohms. Camera B required 750 ohms at room temperature for reliable operation.

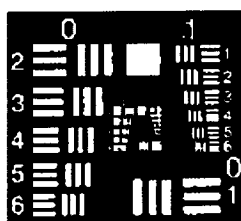


The mechanics will probably become much stiffer at the low temperatures that may occur on the flight. We therefore suggest that the focuser stepper motors be operated at full rated current for the short time that they are actually in motion and then be set back to some low holding current when at standby to conserve battery. The holding current, however, needs to be sufficient to prevent back slippage due to the springiness of the coupling.

# Resolution Target Testing

## General Description

One of the most definitive tests of resolution of any imaging system is to image a precision test target at the appropriate object distance. For our purposes, this means that we need to image the test target at infinity. To simulate this, we placed a USAF 1951 chrome on glass target reticle at the prime focus of a reflective collimator and illuminated it with white light through an opal diffusing screen. The target, as shown below, is comprised of seven groups of six elements each of ever-narrower sets of parallel lines and spaces arranged in a square spiral. For example, the top left pattern below is group 0 element 2 of the target while the top right pattern is group 1 element 1. From the table below, we see that group 0 element 2 is spaced at 1.12 lines per mm and group 1 element 1 is spaced at 2.00 lines per mm on the target. The idea is to find the closest spacing which is barely resolved by the system.



USAF Chrome on Glass  
Resolving Power Target

NUMBER OF LINES PER MILLIMETER IN USAF RESOLVING POWER TEST TARGET 1951 GROUP NUMBER ON TRANSPARENT TARGETS ONLY											
Group Number											
	-2	-1	0	1	2	3	4	5	6	7	
Element	1	0.250	0.500	1.00	2.00	4.00	8.00	16.0	32.0	64.0	128.0
	2	0.280	0.561	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144.0
	3	0.315	0.630	1.26	2.52	5.04	10.1	20.16	40.3	80.6	161.0
	4	0.353	0.707	1.41	2.83	5.66	11.3	22.62	45.3	90.5	181.0
	5	0.397	0.793	1.59	3.17	6.35	12.7	25.39	50.8	102.0	203.0
	6	0.445	0.891	1.78	3.56	7.13	14.3	28.5	57.0	114.0	228.0
IMAGE FORMAT - 1/4 to 228 LINES/mm TARGET											

Target Spacing Specifications

The target is placed at the focus of a reflective collimator with a focal length of 2718mm, placing its apparent image at infinity. A telescope calibrated for this purpose checked the apparent object distance. The spacing of the lines in each group and element of the target now has an apparent spacing at the entrance of the camera lens in arc seconds as calculated in the table below. Also shown are the lines per mm and the equivalent spacing in microns at the CCD with the 180mm focal length camera lens in place. We have highlighted the element approximating the dimension of the pixels in our CCD: 6.8 microns or group 3 element 3. The Niquist resolution limit would be two pixels corresponding to group 2 element 3 with our collimator and a 180mm camera lens.

Target / Collimator / CCD Dimensions

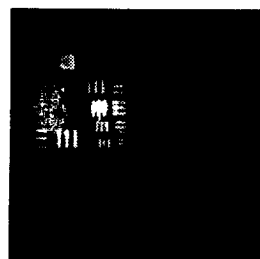
Group.#	L / mm	Col sec"	CCD / mm	CCD micron
1.1	2.00	37.9507	30.2000	33.1126
1.2	2.24	33.8846	33.8240	29.5648
1.3	2.52	30.1196	38.0520	26.2798
1.4	2.83	26.8203	42.7330	23.4011
1.5	3.17	23.9437	47.8670	20.8912
1.6	3.56	21.3206	53.7560	18.6026
2.1	4.00	18.9753	60.4000	16.5563
2.2	4.49	16.9045	67.7990	14.7495
2.3	5.05	15.0300	76.2550	13.1139
2.4	5.66	13.4101	85.4660	11.7006
2.5	6.35	11.9530	95.8850	10.4292
2.6	7.13	10.6454	107.663	9.28824
3.1	8.00	9.48767	120.800	8.27815
3.2	8.98	8.45227	135.598	7.37474
<b>3.3</b>	<b>10.1</b>	<b>7.51499</b>	<b>152.510</b>	<b>6.55695</b>
3.4	11.3	6.71694	170.630	5.86063
3.5	12.7	5.97649	191.770	5.21458
3.6	14.3	5.30779	215.930	4.63113

The image of the target under even illumination was carefully focused and examined with the camera software under extreme magnification so as to examine the image at the pixel level. Under these conditions, we were able to barely resolve group 2 element 6 with camera A and group 2 element 5 for camera B for target resolutions of 10.6 and 11.9 arc seconds respectively. This is marginally better than the Niquist limit, which implies that the pixels size, not the optical focus or resolution, is the limiting factor. Based on this test, camera A is marginally sharper than camera B.

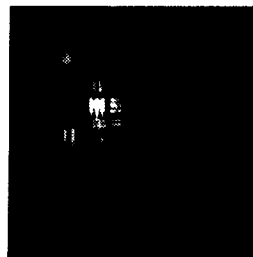
## Camera A USAF Target Tests

As noted above, camera A was able to barely resolve group 2 element 6 for a target resolution of 10.6 arc seconds. There was no noticeable difference between the focused target at the center of the CCD and at the corner, which implies a flat focal surface as well as excellent lens coverage.

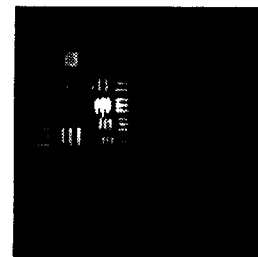
Camera A was also tested with different filters in place to see what effect there would be on the image. Combinations tested were (1) no filter, (2) red 25 filter and (3) #89b filter. Best focus resulted in (1) group 2 element 6 with no filter or 10.6 arc second resolution. (2) group 2 element 5 or 11.9 arc second resolution. (3) group 2 element 3 or 15 arc seconds: the Niquist limit. Since the exposure was not adjusted to compensate for the density of the filter, we are uncertain whether the effect is due to the wavelength effects on the lens or to exposure effects. Portions of these tests are reproduced below.



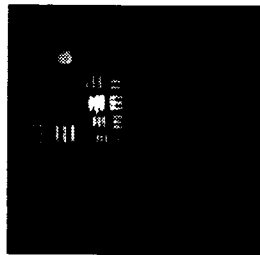
89af1952.gif



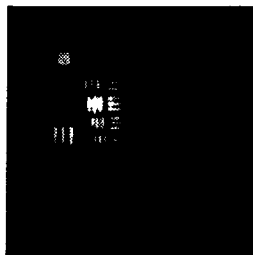
89af1954.gif



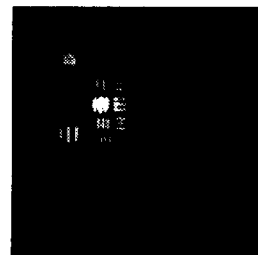
89af1958.gif



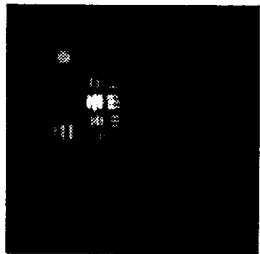
89af1960.gif



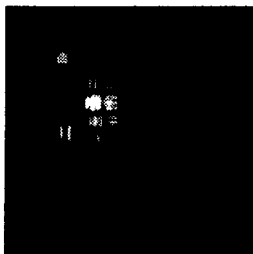
89af1962.gif



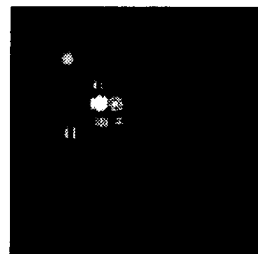
89af1964.gif



89af1966.gif

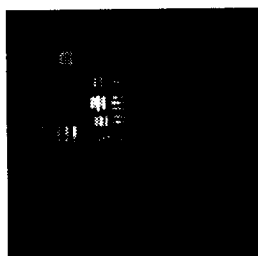


89af1968.gif

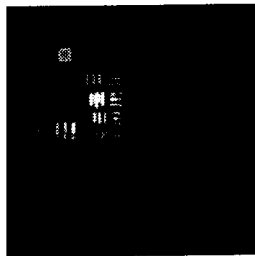


89af1970.gif

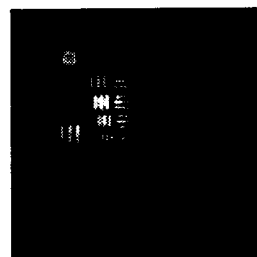
Camera A past focus series, #89b filter



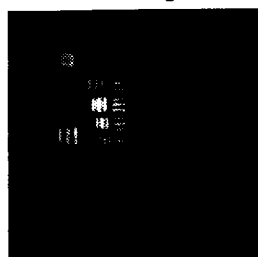
**faf1970.gif**



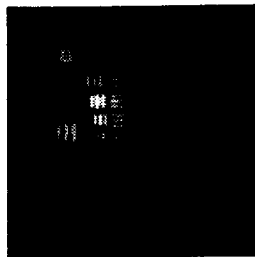
**faf1972.gif**



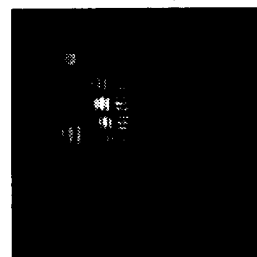
**faf1974.gif**



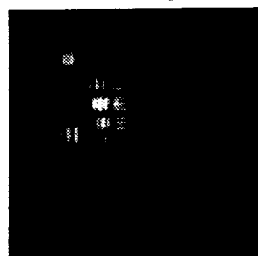
**faf1976.gif**



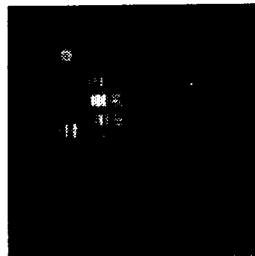
**faf1978.gif**



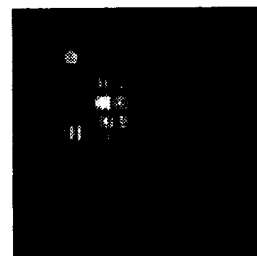
**faf1980.gif**



**faf1982.gif**



**faf1984.gif**



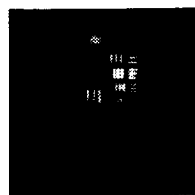
**faf1986.gif**

Camera A past focus series, no filter



## Camera B USAF Target Tests

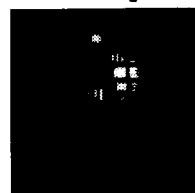
As noted above, camera A was able to barely resolve group 2 element 5 for a target resolution of 11.9 arc seconds. There was no noticeable difference between the focused target at the center of the CCD and at the corner, which implies a flat focal surface as well as excellent lens coverage. Although Camera A tested marginally better, the difference is not significant. A portion of this test is reproduced below.



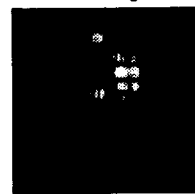
faf1950.gif



faf1956.gif



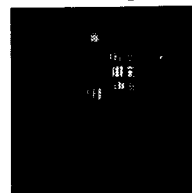
faf1962.gif



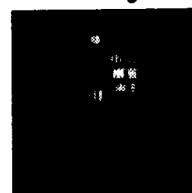
faf1968.gif



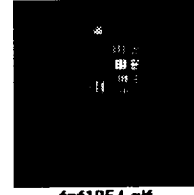
faf1952.gif



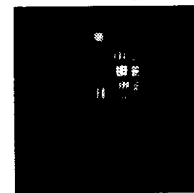
faf1958.gif



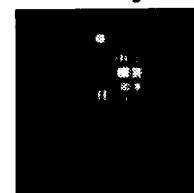
faf1964.gif



faf1954.gif



faf1960.gif



faf1966.gif

Camera B past focus series, no filter

# Sky Star Testing / Plate Scale

A complete twilight series and star test data set could not be obtained due to the delays in final camera assembly construction, in a large part due to priorities at the machine shop. This consultant's request to bring them to the Von Braun Observatory for such testing in conjunction with the lunar satellite crash was denied by Jeff Apple and Kurt Dietz: "we are not going to risk expensive flight hardware". They did, however, operate one of the cameras, we are not sure which one, at SSL aimed at Vega in order to test the plate scale of the system. Six exposures were taken ranging from 2 seconds to 1/8 second as detailed below. The focus in this series was poor with the star photons generally in about 20 pixels. In all images but vega6.tiff the stars were over exposed leading to centroiding difficulties. In that image Vega was still over exposed, but then it is the mv0 standard star.

## Vega Observations, SSL Loading Dock, 9/29/99

File	Time	Length	Alt deg	Alt min	Alt sec	Alt	Az hour	Az min	Az sec	Az
Vega1	21:44:00	2	63	51	42	63.8617	71	20	22	71.3394
Vega2	21:47:30	3	64	32	44	64.5456	71	21	39	71.3608
Vega3	21:49:15	1	64	53	15	64.8875	71	21	58	71.3661
Vega4	21:49:45	0.5	64	59	7	64.9853	71	22	0	71.3667
Vega5	21:51:45	0.25	65	22	33	65.3758	71	22	1	71.3669
Vega6	21:52:15	0.125	65	28	25	65.4736	71	21	58	71.3661

Gain = 3

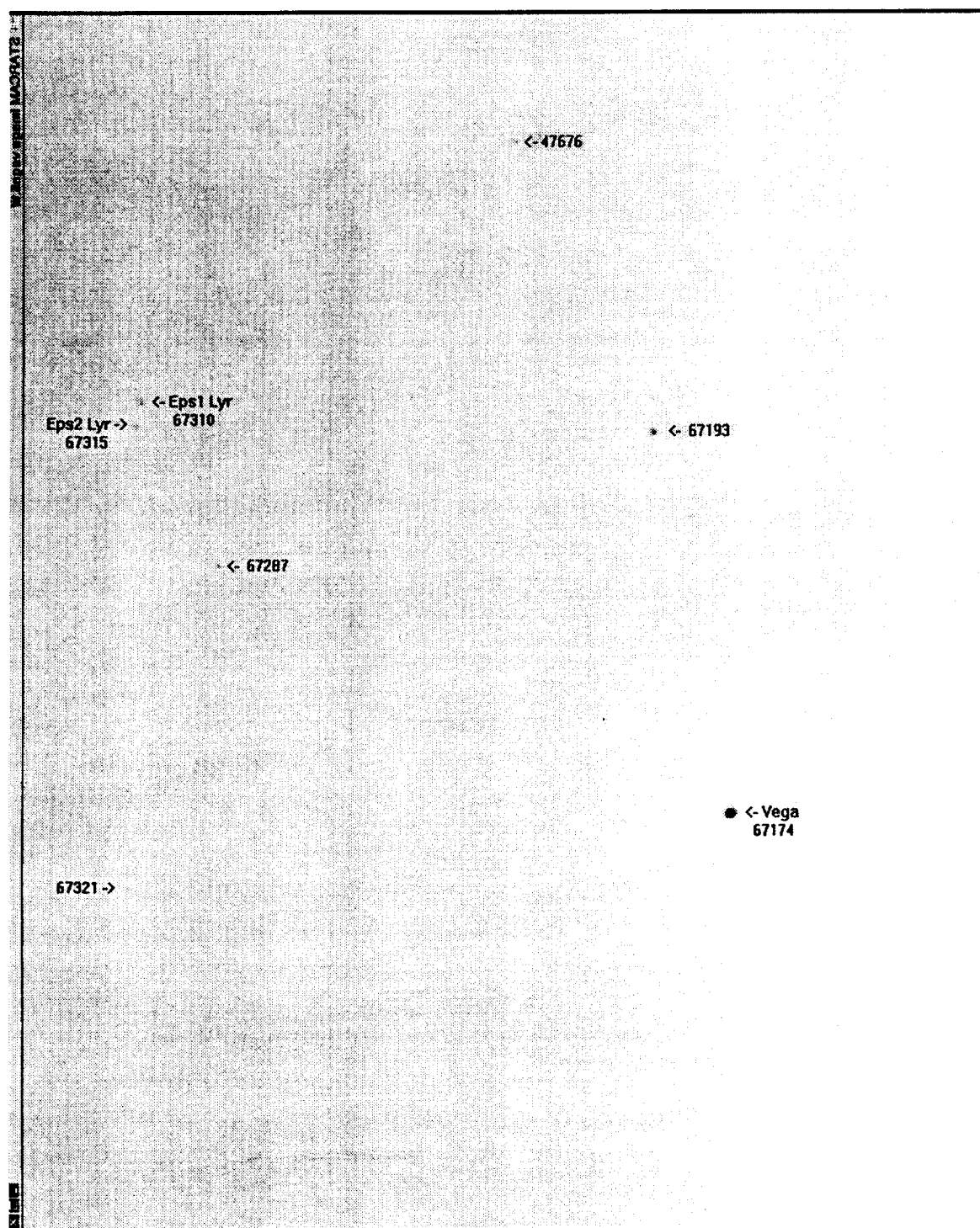
Alt-Az for Vega, not for center of image

Vega RA = 18h36m56s, Dec = 38d47'01" (J2000) SAO67174

Object	Mag (V)	Raw Count	Net Count
SAO67193	6.04	33849	12464
Eps1 Lyr	5.06	26643	2753
Eps2 Lyr	5.14	27049	3086
SAO67302	6.54	26604	2396
SAO67287	6.45	25297	1700
SAO47678	7.77	23344	1590

### Notes:

1. Exposure was 0.125 seconds
2. Gain setting was 3
3. Aperture filter label B-W 72E 092



Vega6.tif SSL star image. Stars SAO67321 and SAO47676 identities are uncertain.

The above image was examined by centroiding each of the identified stars and comparing their position in the image in pixels with the stars separation in the sky in degrees. The results for five of the stars was extremely consistent, as shown below, while that for two of the stars, SAO67321 and SAO47676, was significantly different. We conclude that we have miss-identified these stars. The image with the deep red filter used is significantly different from the visual one. The plate scale of 0.002165 deg / pixel is consistent with that of 2.1645E-03 deg / pixel for a lens with 180.0mm focal length.

Star / #	*0	*1	*2	*5	*6
	67310	67315	67287	67193	vega
67310		0.0575	0.4233	1.1992	1.685
67315			0.3797	1.2092	1.6633
67287				1.0636	1.335
67193					0.9131
	Deg separation				

x pix	444.28	417.945	594.659	451.797	864.746
y pix	915.693	909.743	827.013	356.549	272.784

67310	0	26.99879	174.5795	559.1945	768.1951
67315		0	195.1207	554.2288	778.0411
67287			0	491.6766	616.5361
67193				0	421.3591
	Pixel Separation				

67310	0.00213	0.002425	0.002145	0.002193
67315		0.001946	0.002182	0.002138
67287			0.002163	0.002165
67193	Deg / Pixel			0.002167
			Average	0.002165

6.8000E-03 Pixel mm  
1.8000E+02 Lens mm  
2.1645E-03 Deg / pix

# Appendix A

## Phase C Redefinition:

4) Prepare startracking camera assembly procedures and supervise system assembly

- \* This is general oversight only to verify overall performance of agreed assemblies and components.

(5) Startracking camera system tests

A) Lab tests, flatfields, calibration and system performance qualification tests

- \* Propose optic bench / collimator tests of resolution and focus + flatfield production and evaluation.

B) Perform twilight sky tests and evaluate full system performance and accuracy

- \* Propose that these tests take place at the Von Braun Observatory.

C) Prepare qualification test report and attend qualification review

- \* We need to define qualification.

(6) Final platform integration and full startracking system checkout and flight preparedness checkout

- \* This will not be possible within the time constraints of this contract. Suggest separate contract.